Extrapolation of Spacecraft Vibration Test Data

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Summary

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- Examples of Spacecraft Vibration Testing vs. Analysis Problems
  - MER - Under Prediction of Frequencies
  - HESSI - New Technology in Old Facility
  - GRACE - Cross Axis Coupling
  - GALEX - High Internal and Coupling Damping In Spacecraft Test

Objective

The objective of this research is to develop FEM compatible methodologies to:

1) **capture** the knowledge gained in vibration tests of spacecraft and other complex structures, and then to

2) **extrapolate** this knowledge to **predict** the dynamic behavior of new designs.

Justification

Dr. Edward Stone, the previous director of the Jet Propulsion Laboratory (JPL), told some students in the wake of the failures of two Mars spacecraft in 1999, **"The key thing is to test. Build it, test it, and test it some more. Because once it's gone, it's too late."**

But,,,,Vibration tests of flight spacecraft are difficult to justify because they are: 1) expensive, 2) time consuming, 3) risky, 4) late in the program, and 5) of little use to future programs.

- To be succeed in today's environment of many smaller projects, the knowledge gained in each project must be captured, accumulated, and made available to new projects.
- The emphasis in the spacecraft development, design, and verification process is more and more on analysis. FEM is the dominant analysis tool in the structures area, now and in the foreseeable future.
- Extrapolation techniques are also needed to project from vibration tests of DTM to flight configurations, and from flight to on-orbit configurations

Related Work

- Extrapolation techniques: Mahaffey-Smith, Burst-Himelblau, Eldred, Curtis, Barrett, Franken, etc.
- The Extrap I routine in the SEA program VAPEPS
  - Two five-element SEA templates with different parameters, one for existing system for which data were available, and the other for a future system with no data
  - The Extrap I routine used SEA theory, to extrapolate frequency response measurements from the existing system to the new system.
- FEM correlation, model updating, reconciliation, etc.
- Substitution analysis and impedance modeling
- Metamodels and response modeling (SNL and LANL)
- Data bases and tools, e.g. VISPERS and commercially available software
- Other ?????????

Two Proposed Extrapolation Approaches

I. Modal Mass Acceleration Curve Method
II. Reconciliation Method

System A	**System B**
Theoretical FEM	Theoretical FEM
Experimental data	No data!!!!!

In both approaches, ratios of experimental (x) to theoretical (t) modal parameters: natural frequency fn, damping quality factor Qn, and effective mass Mn are extrapolated from A to B:

fn_{Ax} / fn_{At}	x	fn_{Bt}	=	fn_{Bp},	projected values
$Qn_{Ax}/Qn_{At})$	x	Qn_{Bt}	=	Qn_{Bp},	"
Mn_{Ax}/Mn_{At}	x	Mn_{Bt}	=	Mn_{Bp},	

I. Modal Mass Acceleration Curve Method

1. Plot measured normalized modal acceleration versus theoretical effective modal mass for existing system A. (The mean-square modal acceleration is used for random vibration tests.)
2. Use theoretical modal parameters for new system B to take data off the MMAC and to predict the responses of system B.

From Mile's Eq., the mean-square modal acceleration is:

$$E(a_n^2) = (\pi/2)S_o f_n Q_n M_n/M_{nn}$$

$$E(a_n^2) / [\ (\pi/2)S_o f_n Q_n M_o/M_{nn}] = M_n/M_o$$

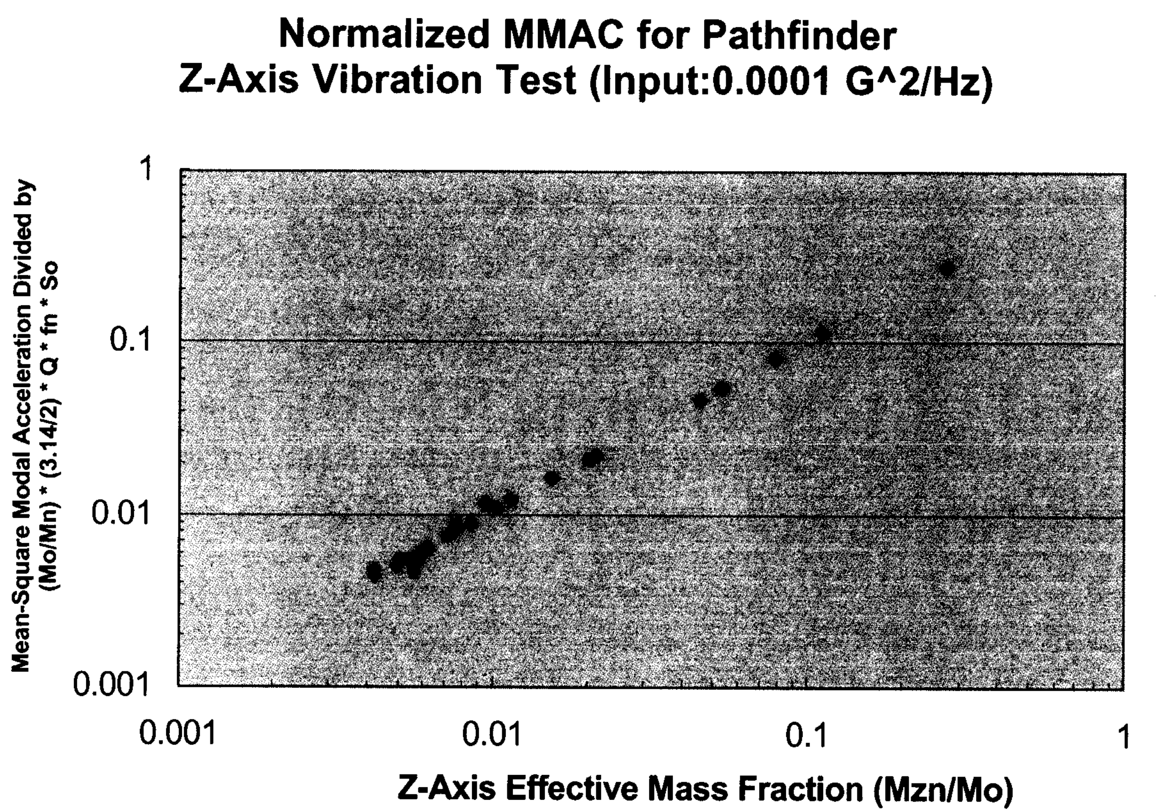
$$E(a_n^2)]_x / E(a_n^2)]_t = f_{nx}/f_{nt} * Q_{nx}/Q_{nt} * M_{nx}/M_{nt}$$

where: a_n is modal acceleration, S_o is input acceleration power spectral density, f_n is the modal resonance frequency, Q_n is modal damping quality factor, M_n is modal effective mass, and M_{nn} is modal mass, which is usually normalized to unity.

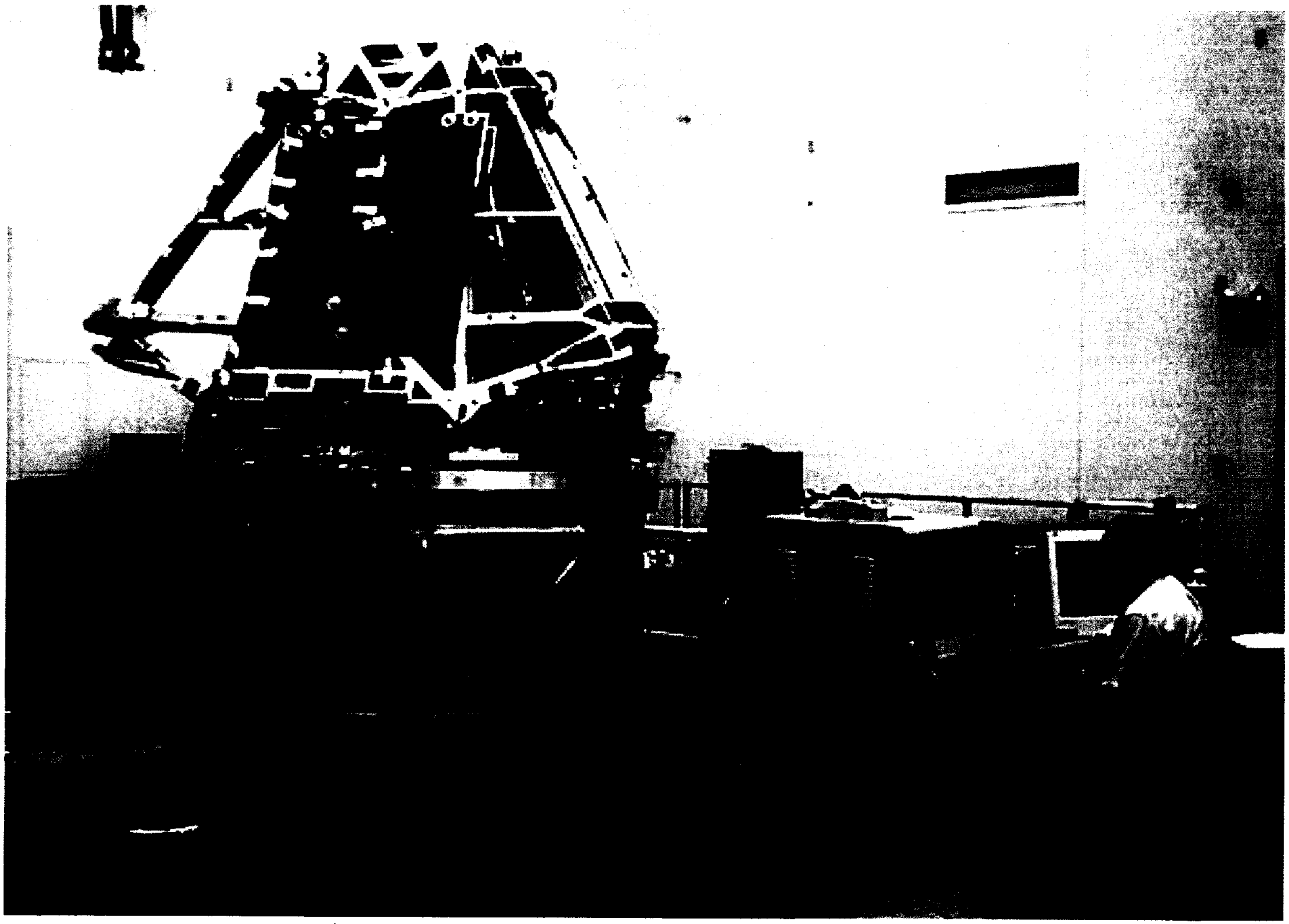
Theoretical (FEM) MMAC *

Random Vibration Test of Mars Pathfinder DTM Lander
Vertical, Apex-Mount Configuration

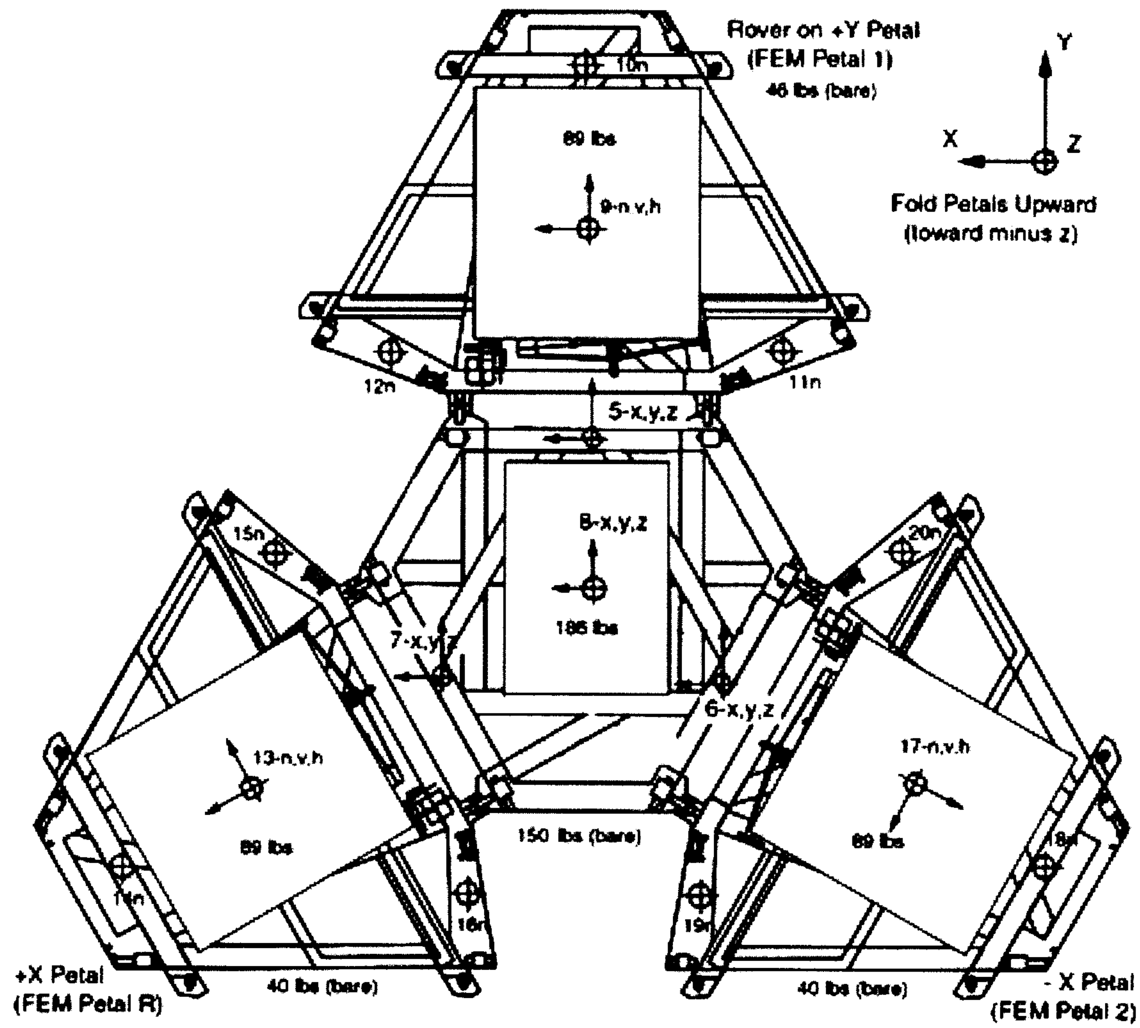
Mary Baker, ATA, from 2001 S/C & L/V TIM



Random Vibration Test of Mars Pathfinder DTM Lander
(Vertical, Base-Mount Configuration)



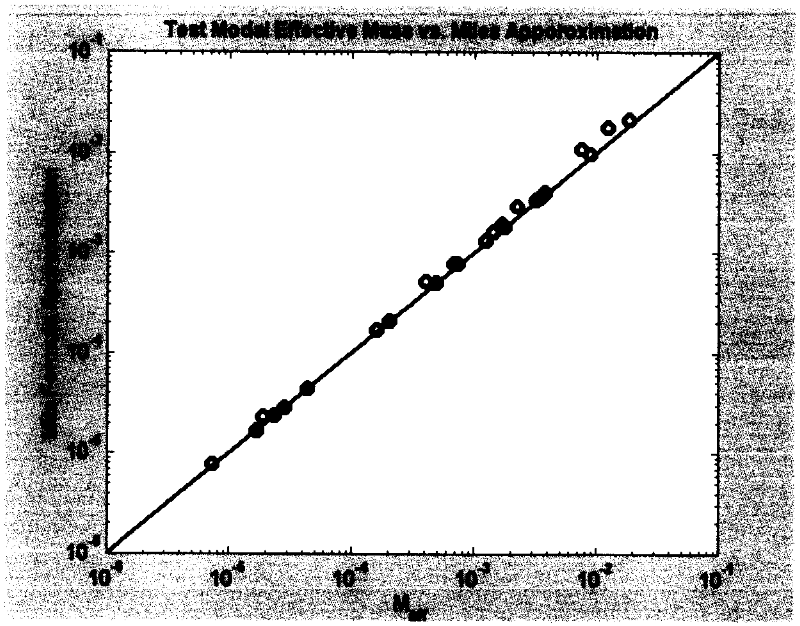
Schematic of Pathfinder DTM Lander with Mass Simulator Plates (Total Weight ~730 #)



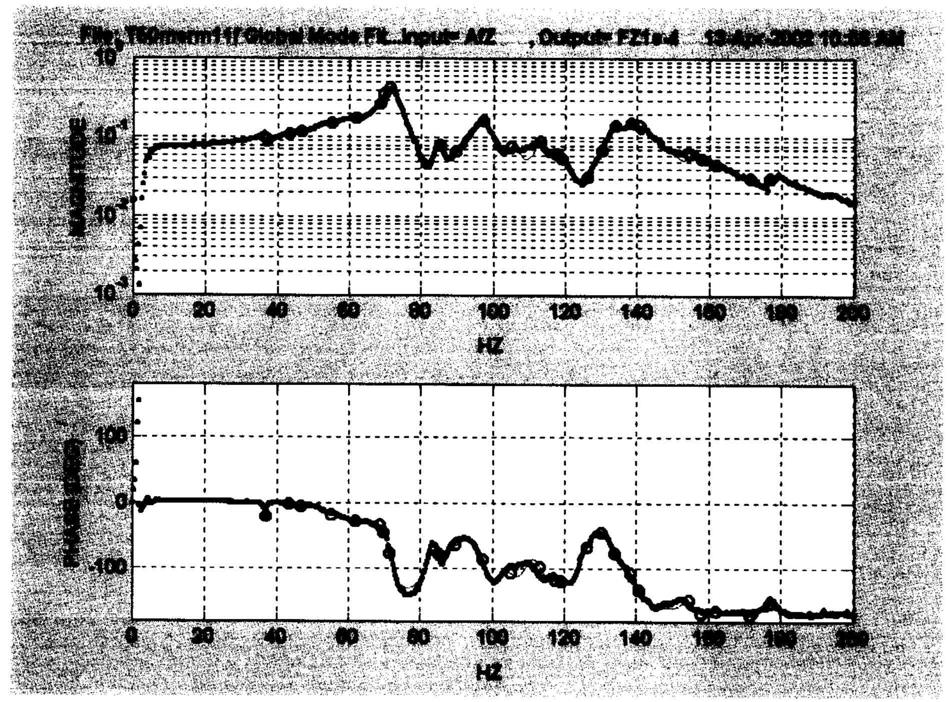
Experimental MMAC *

Random Vibration Test of Mars Pathfinder DTM Lander
(Vertical, Base-Mount Configuration)

*Bob Coppolino, MAC



Experimentally Determined MMAC



Comparison of Measured and Reconstructed Base Apparent Mass

Comparison of Experiment and Theory
Random Vibration Test of Mars Pathfinder DTM Lander
(Vertical, Base-Mount Configuration)

MMAC's for Pathfinder DTM Rover/Base Vertical Vibration Test tds-6/20/02

X=Experiment Run 50 Data -------

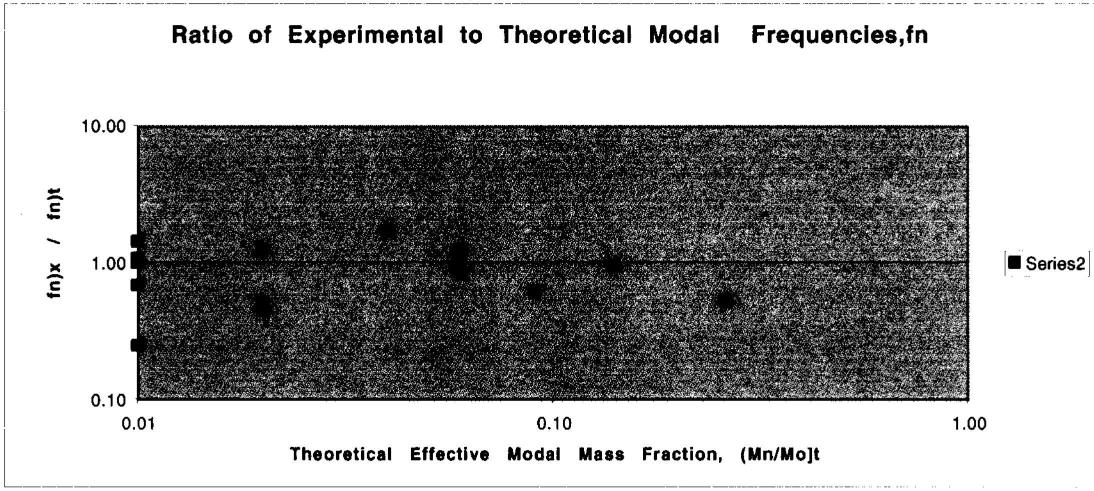
Mode*	So [G^2/Hz]	fn	Qn	Mn/Mo
8	0.0001	71.5	19	0.26
7	0.0001	69.8	6	0.17
11	0.0001	97.3	16	0.12
5	0.0001	61.9	7	0.11
18	0.0001	134	27	0.05
19	0.0001	138.6	26	0.05
13	0.0001	113.2	20	0.04
4	0.0001	55.2	11	0.03
6	0.0001	68.8	21	0.02
9	0.0001	85.2	31	0.02
10	0.0001	89.7	14	0.02
12	0.0001	105.2	20	0.02
20	0.0001	141	17	0.02
1	0.0001	36.8	48	0.01
15	0.0001	119.3	23	0.01
21	0.0001	154.6	43	0.01
			Total =	0.96

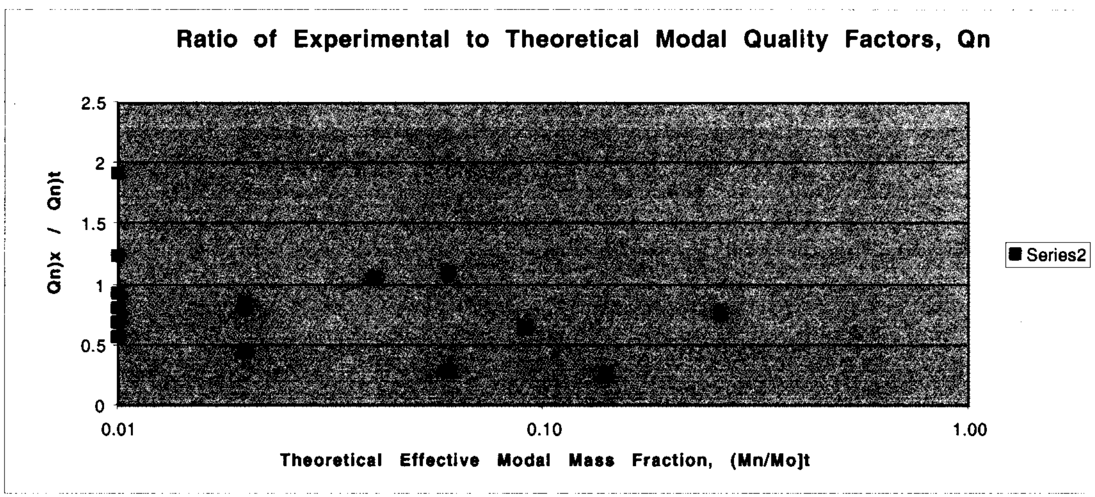
T=Theory FEM BWT 6/19 10:35AM

Mode*	So [G^2/Hz]	fn	Qn	Mn/Mo
19	0.0001	138	25	0.26
4	0.0001	75.8	25	0.14
26	0.0001	157	25	0.09
3	0.0001	71.5	25	0.06
15	0.0001	111	25	0.06
8	0.0001	83.5	25	0.04
11	0.0001	90.7	25	0.02
14	0.0001	110	25	0.02
24	0.0001	152	25	0.02
1	0.0001	60.7	25	0.01
6	0.0001	82.6	25	0.01
12	0.0001	102	25	0.01
20	0.0001	141	25	0.01
23	0.0001	149	25	0.01
31	0.0001	173	25	0.01
			Total =	0.77

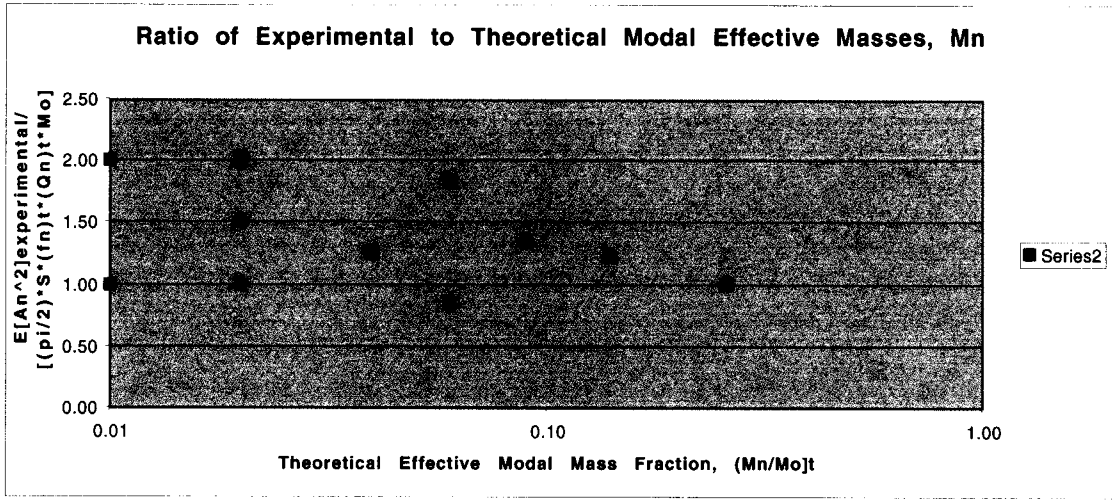
* Modes with effective mass, Mn/Mo, greater than or equal to 0.01, ordered greatest to least value of Mn/Mo

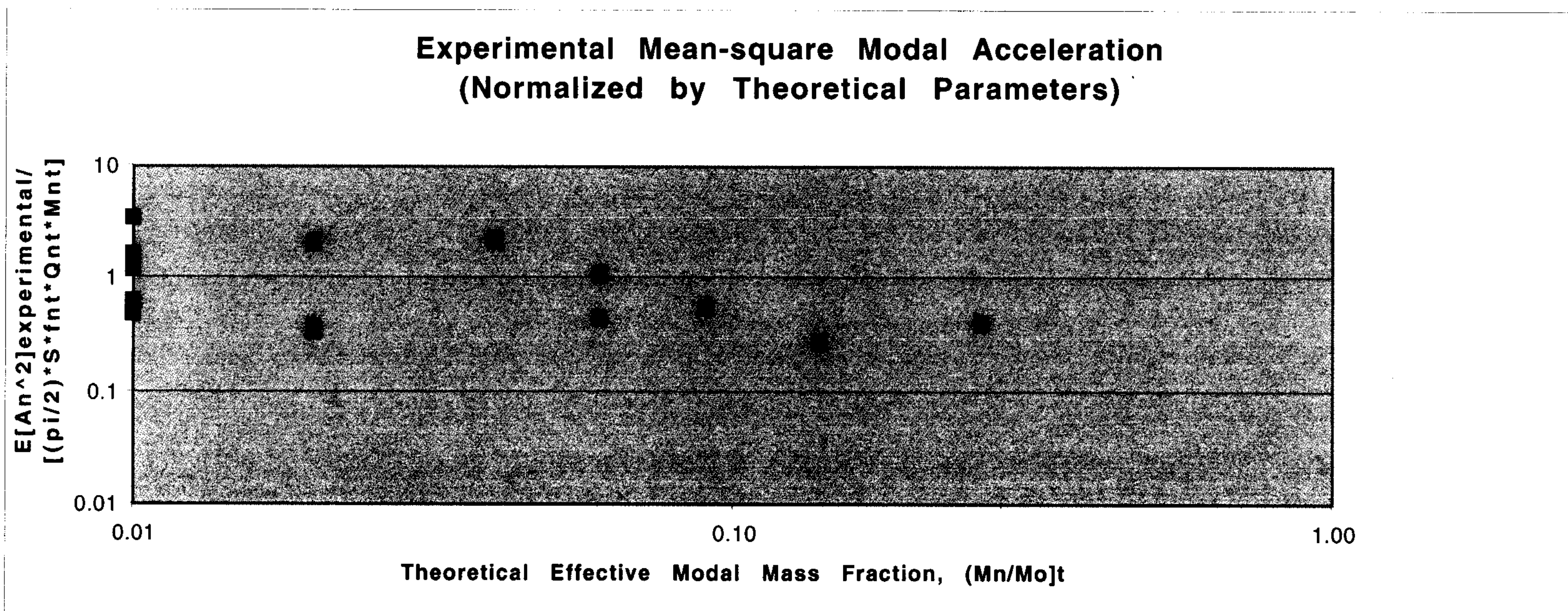
Frequency and Damping Factors in Normalized MMAC





Effective Mass Factor and Normalized MMAC



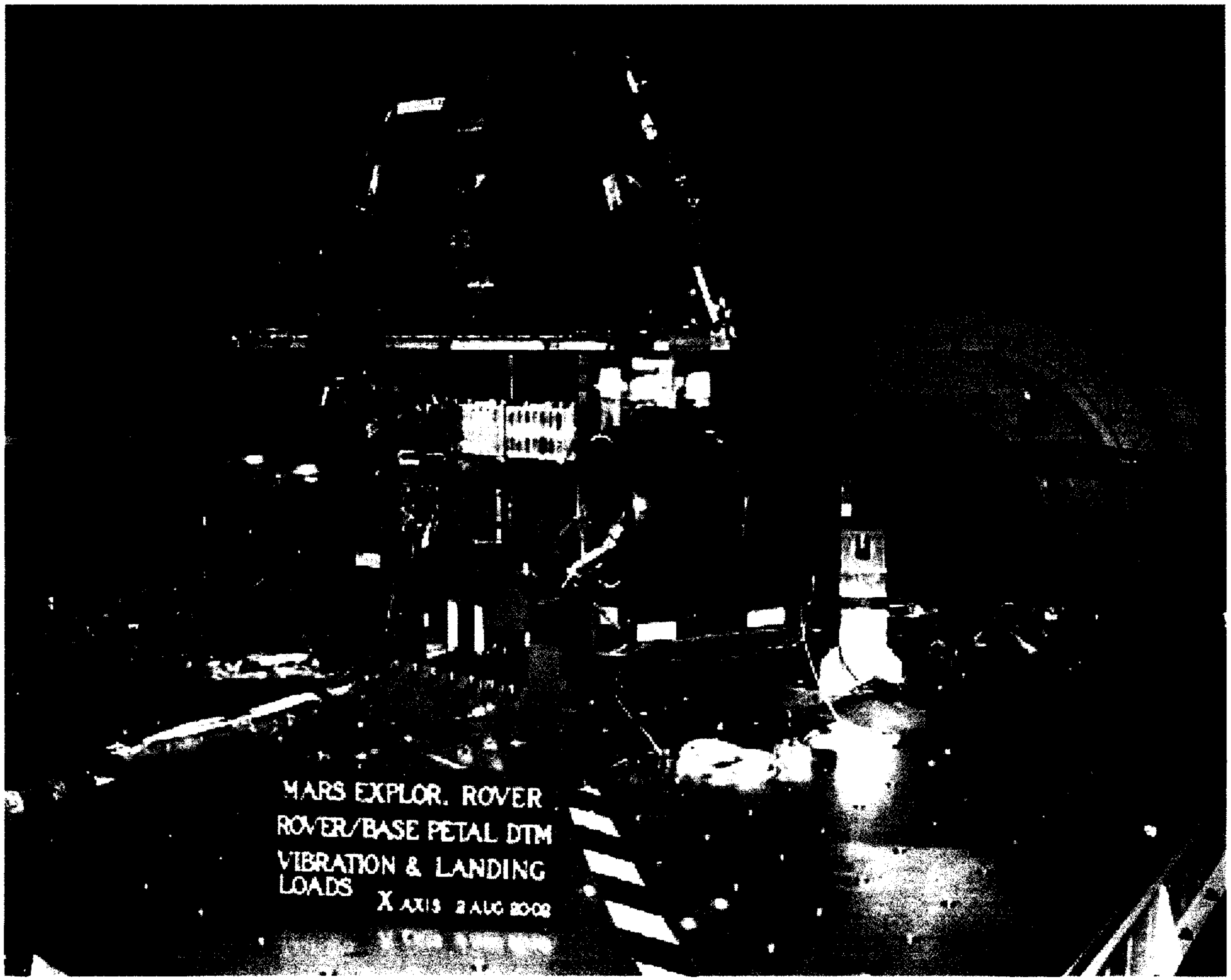


II. Reconciliation Method

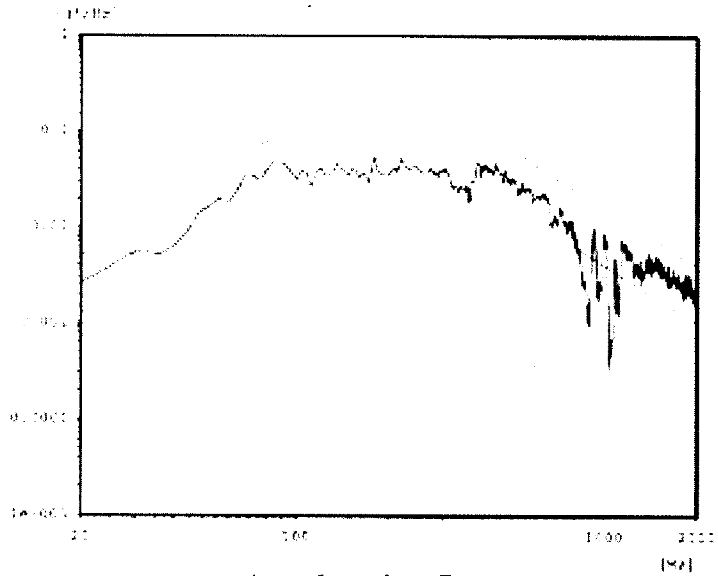
(Method to be used to extrapolate DTM Rover/Base Vibration Test Data to the Flight Hardware Tests)

1. Calculate the ratio of measured to theoretical modal parameters (frequency, damping, and effective mass) for an existing system A.
2. Reconcile the measured and theoretical modal parameters of system A by changing the physical mass and stiffness matrices.
3. Project the system A measurements to system B by multiplying the aforementioned ratios of unreconciled system A modal parameters by the theoretical values for system B.
4. Reconcile the projected and theoretical modal parameters of system B by changing it's mass and stiffness matrices in a manner similar to that which reconciled system A.
5. Use the reconciled model of system B to predict it's responses.

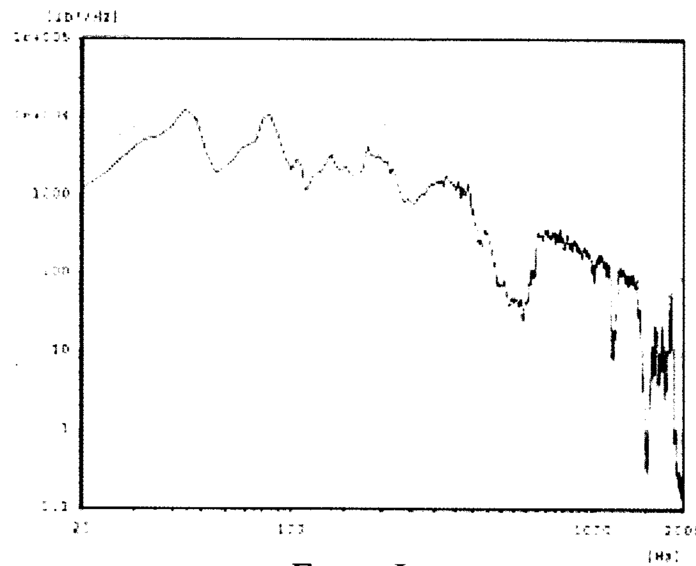
Mars Exploration Rover (MER) Development Test Model (DTM) Rover/Base Petal Vibration Test



Mars Exploration Rover (MER) Development Test Model (DTM) Rover/Base Petal Vibration Test Data

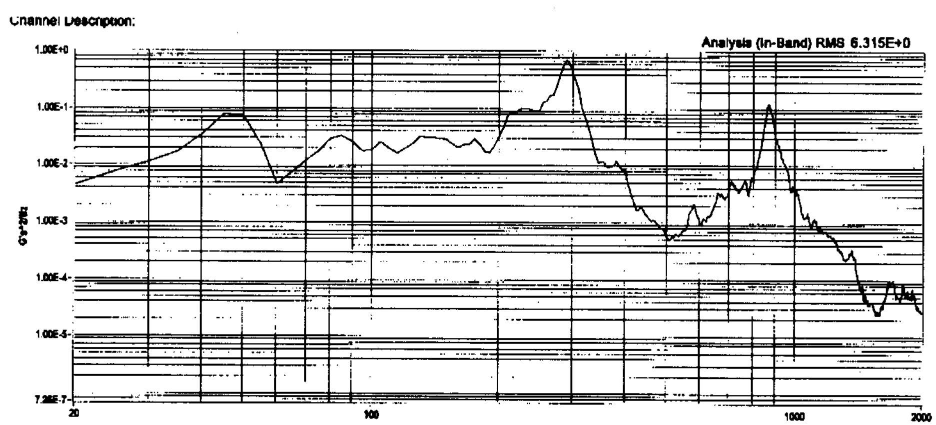


Acceleration Input

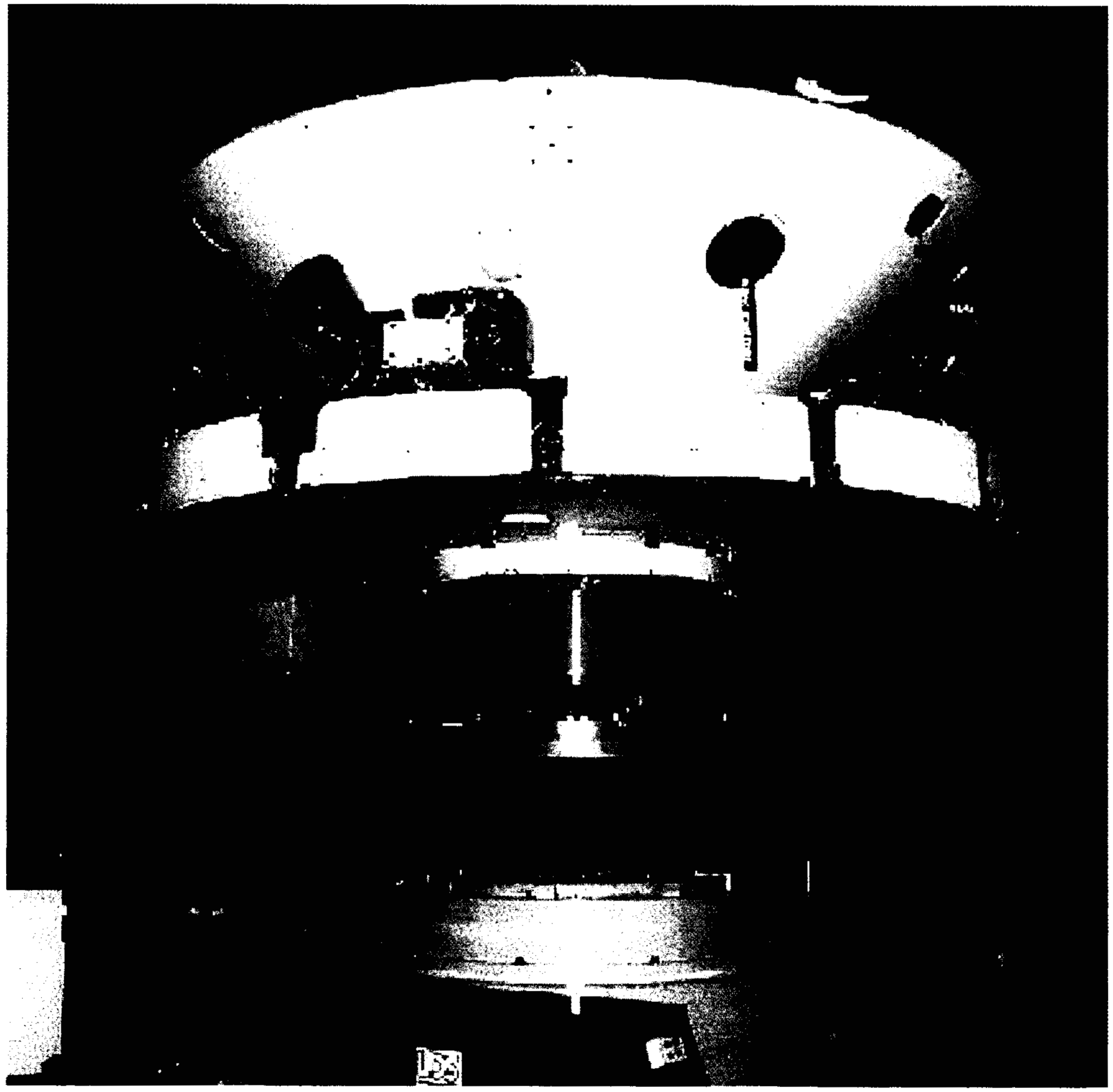


Force Input

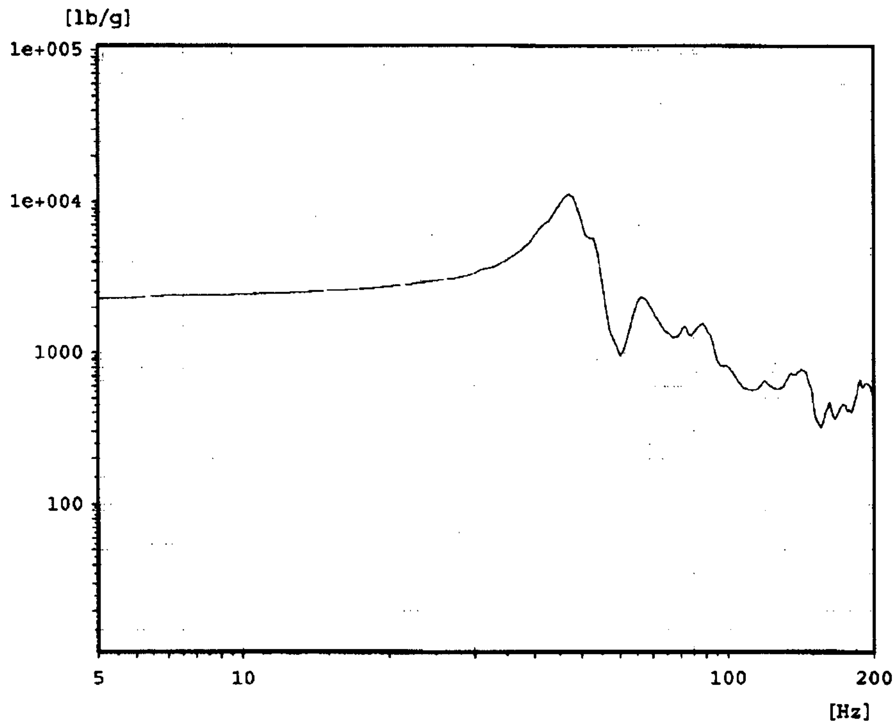
Cross-Axis (Y) Response of MiniTES Instrument Mass Simulator



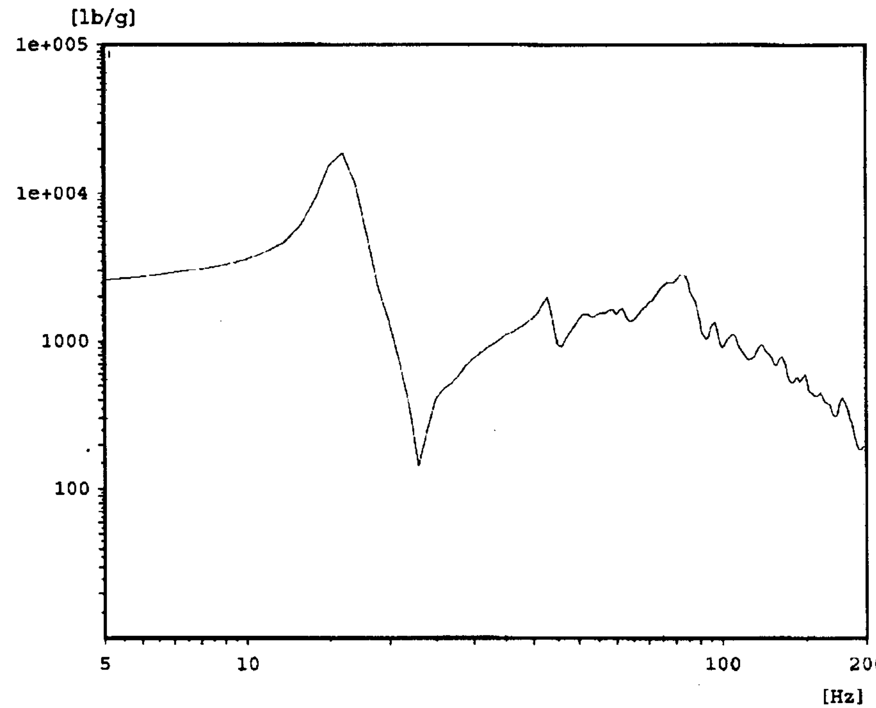
Vibration Test of Mars Exploration Rover (MER) Flight Spacecraft #1



Measured and Predicted Frequencies of Fundamental Vibration Modes of MER1 Spacecraft



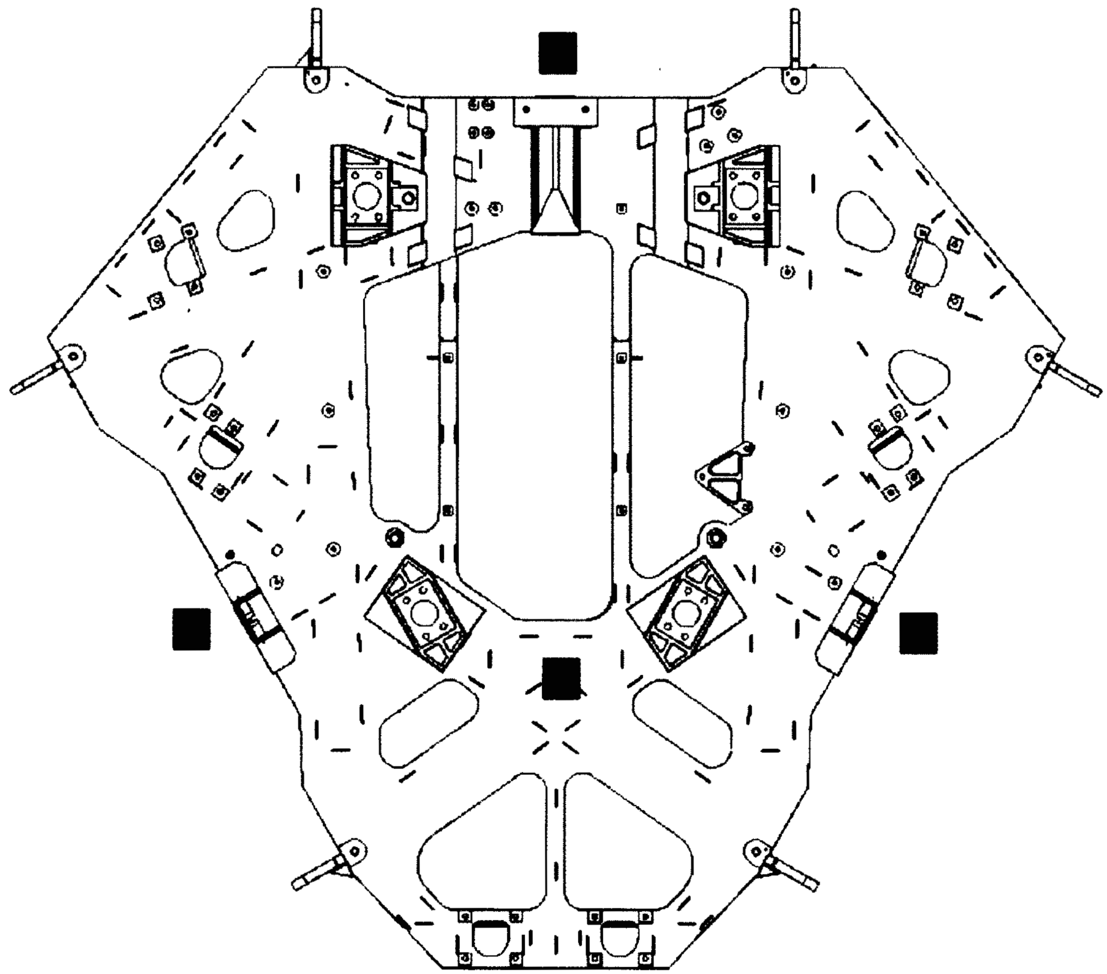
Vertical Axis -- Force/Acceleration
Measured -- 48 Hz
Predicted -- 40 Hz



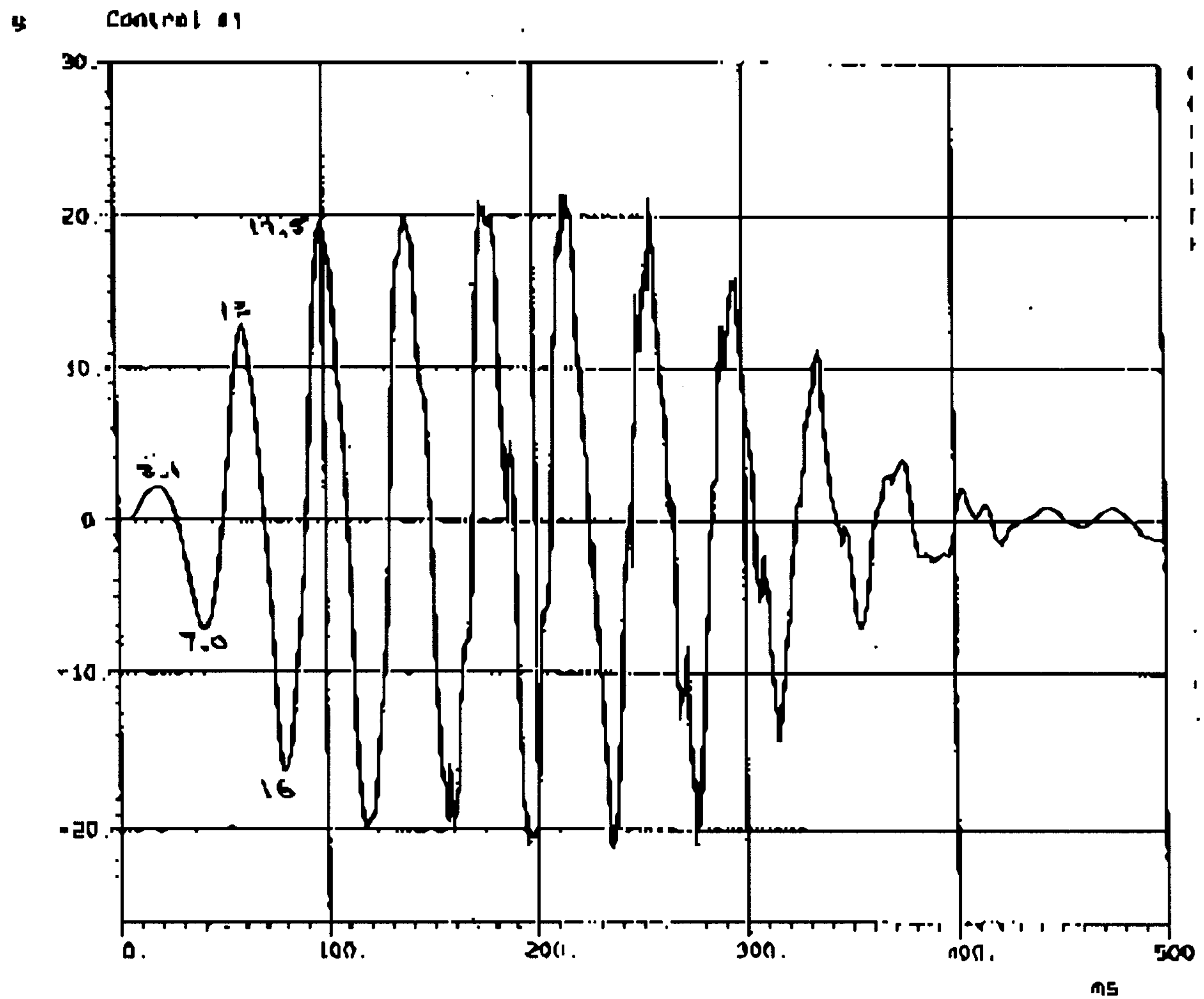
Lateral Axes -- Force/Acceleration X
Measured -- 16 Hz X & 17 Hz Y
Predicted -- 14 Hz X & Y

Predicted Frequencies were ~20% too low, primarily because stiffness of face sheets of composite panels was neglected.

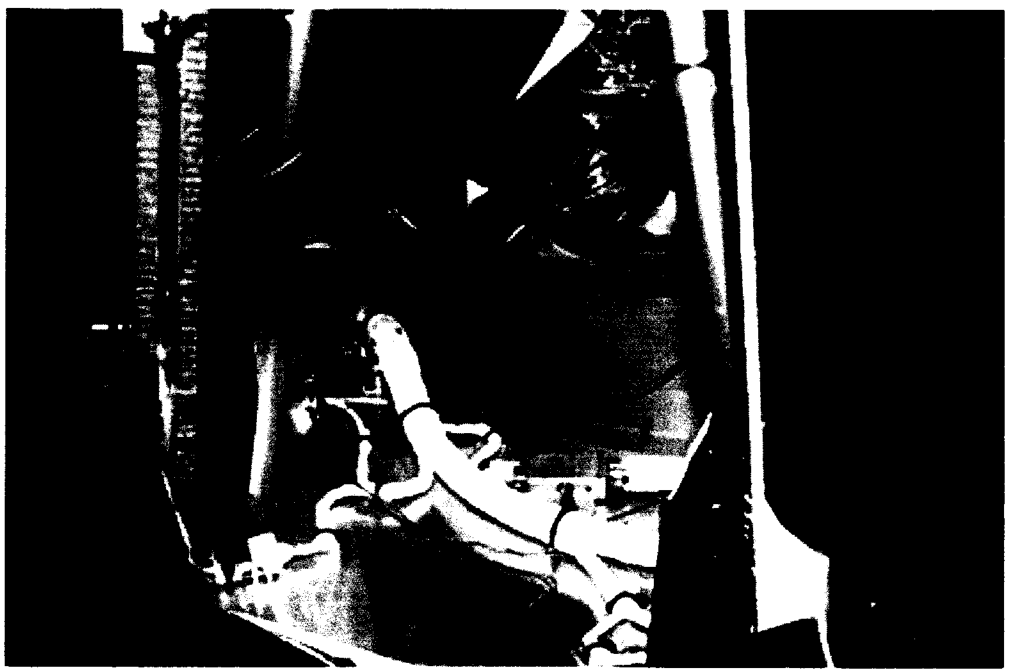
Mars Exploration Rover (MER) Base Petal



Inadvertent 20 G Pulse During HESSI Quasi-static Load Test

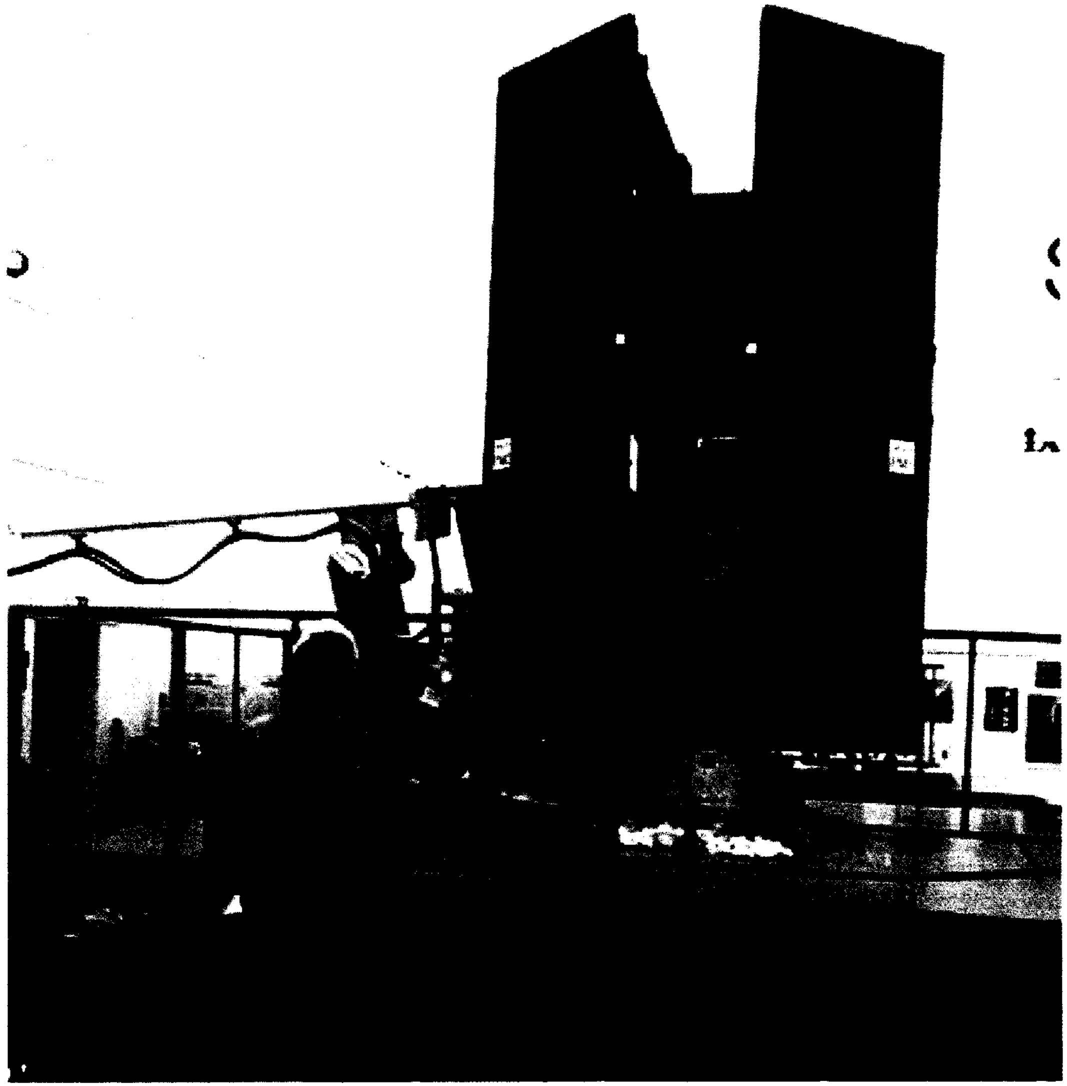


HESSI Spacecraft Over Test Incident

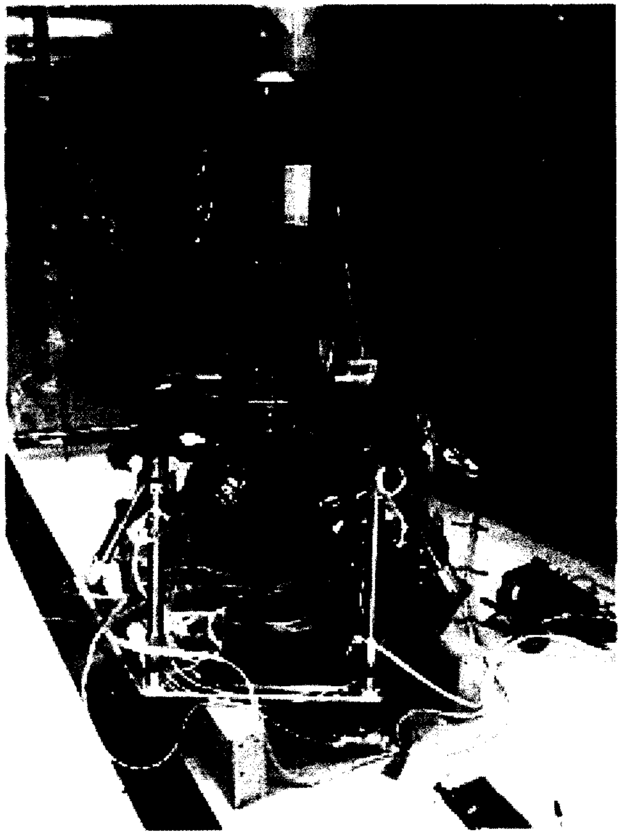


Vertical Vibration Test of GRACE Spacecraft

(Cross-Axis Coupling of Two Spacecraft)



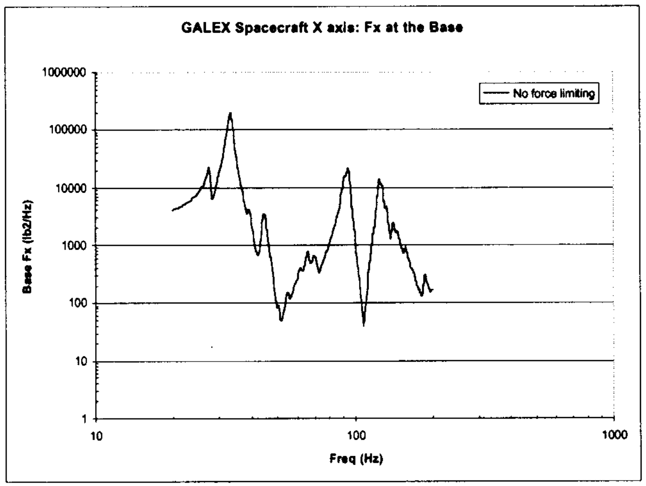
GALEX Spacecraft Vibration Tests

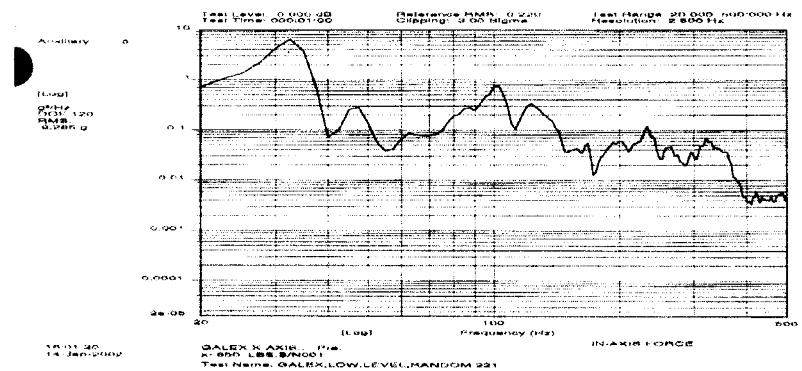


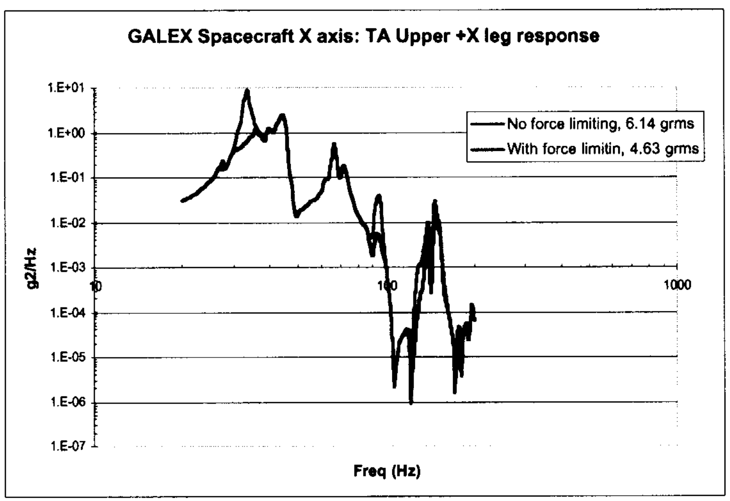
Telescope Vibration Test

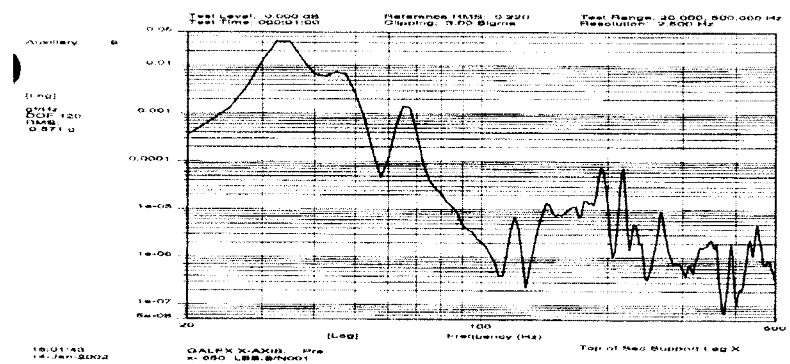
Instrument Vibration Test

GALEX Spacecraft Vibration Test Analyses and Data









Full Level FEM Analyses

Low Level Test data

Conclusions

- "Interpolation is dangerous; extrapolation is insane."
- Two techniques for extrapolating vibration test data have been proposed, one based on the MMAC and the other based on reconciliation.
- A hybrid MMAC approach was investigated using an FEM model and data for a vibration test of the MARS Pathfinder DTM Lander, and the results using effective mass and frequency scaling were poor. Mode Shape?
- The reconciliation approach is more rational and takes advantage of conventional model updating techniques, but it is complex.
- The reconciliation approach will be evaluated using vibration test data obtained on the DTM and Flight MER Rover/Base-Petals
- MER Spacecraft Vibration Test Showed Value of Base Drive Modal Testing
- HESSI Incident Resulted from Applying New Technology in Old Facilities
- GRACE Spacecraft Test Showed Modal Coupling not in Analyses
- GALEX Spacecraft Vibration Test Showed High Internal and Modal Coupling Damping